$\mu^- \to e^+$ and RMC at $\mu^- \to e^-$ Experiments

Snowmass RF Townhall

LOI 108: M. Aoki[1] D. Grigoriev[2] Y. Kuno[1] M. Lee[3] A. Sato[1] J. Tang[4] A. Teixeira[5] Y. Uchida[6] B. Yeo[7] K. Zuber[8]

LOI 109: R. Bernstein[9] K. Borah[10] R. Hill[9,10] M. MacKenzie[11] P. Murat[9] R. Plestid[9,10]

Osaka University, Japan[1] BINP, Russia[2] IBS, Republic of Korea[3] Sun Yat-Sen University, China[4] Université Clermont Auvergne, France[5] Imperial College London, UK[6] KAIST, Republic of Korea[7] Technische Universität Dresden, Germany[8] FNAL, USA[9] University of Kentucky, USA[10] Northwestern University, USA[11]

October 2, 2020

Introduction

- With the discovery of lepton flavor violation (LFV) in the neutrino sector, the search for charged LFV (CLFV) has renewed theoretical (and experimental) interest

- Some of the strictest limits on these processes come from high intensity muon experiments typically focusing on the channels $\mu \to e\gamma$, $\mu \to eee$, and $\mu\ N \to e\ N$

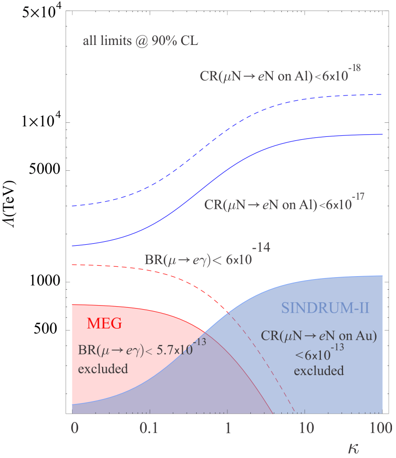
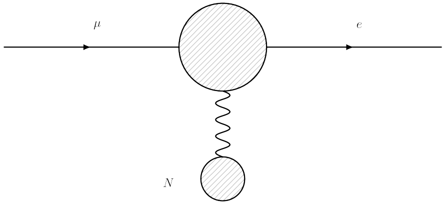


Figure: Parameter space explored [1]

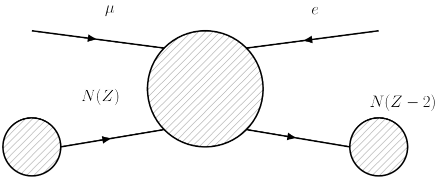
- These processes are allowed in the Standard Model via neutrino oscillations, but with incredibly small branching fractions ($\mathcal{O}(10^{-54})$) [2]

- Many beyond the Standard Model theories predict rates of CLFV measurable at upcoming experiments [3]

$\mu^- \to e^+$ searches



(a) $\mu^- \to e^-$

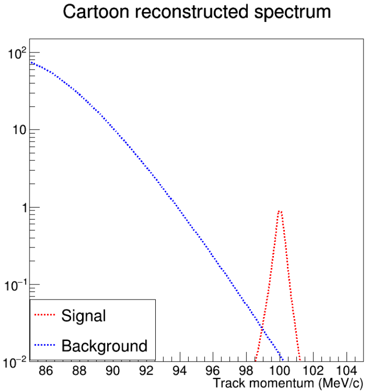


(b) $\mu^- \to e^+$

- Experiments searching for the conversion of a muon into an electron in the field of a nucleus, $\mu^- N(Z,A) \to e^- N(Z,A)$, will typically also be able to search for the both CLFV and lepton number violating (LNV) process of $\mu^- N(Z,A) \to e^+ N(Z-2,A)$, with $\Delta L = 2$
- This process would give insight into possible Majorana mediators, as well as a direct test of off-diagonal matrix elements that $0\nu\beta\beta$ processes wouldn't have access to [4]
- The $\mu^- \to e^+$ channel is the focus of the RF5 letters of interest 108 and 109

Experimental signature

- $\mu^- \to e^-$ is a coherent process with a mono-energetic electron signal, which is a clear signature to search for
- $\mu^- \to e^+$ can be more complicated, as the final state of the target nucleus is not necessarily the ground state
- It is easiest to search for the ground state $\mu^- \to e^+$ transition, which is also a mono-energetic signal



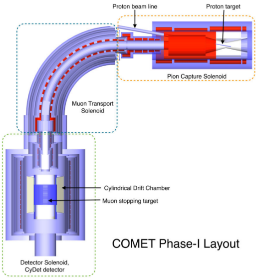
- The current limits for these processes come from the SINDRUM-II experiment:

$$\frac{Br(\mu^- \ Au \to e^- \ Au)}{Br(\mu^- \ Au \to \nu_\mu \ Pt)} < 7 \cdot 10^{-13} \text{ [5]}$$

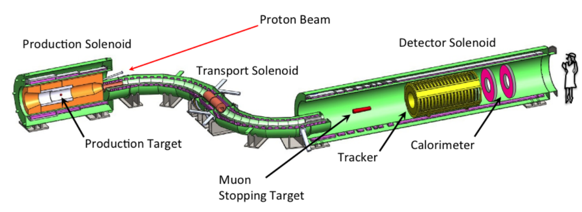
$$\frac{Br(\mu^- \ Ti \to e^+ \ Ca(Ca^*))}{Br(\mu^- \ Ti \to \nu_\mu \ Sc)} < 1.7 \cdot 10^{-12} \text{ GS } (3.6 \cdot 10^{-11} \text{ GDR}) \text{ [6]}$$

where GS is the ground state transition and GDR is the giant dipole resonance transition

Current and future $\mu\ N \to e\ N$ experiments



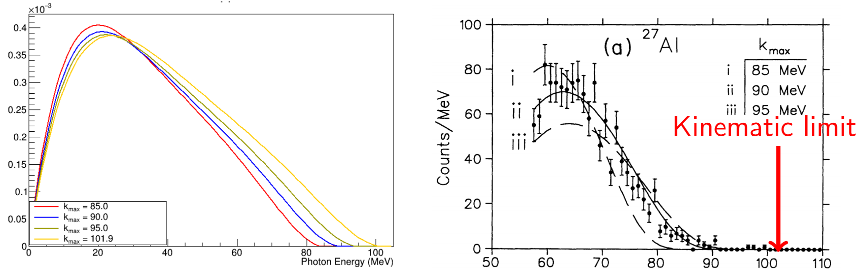
(a) COMET Phase-I [7]



(b) Mu2e [1]

- COMET and Mu2e are currently planned $\mu\ N \to e\ N$ experiments at J-PARC and FNAL respectively
- They will be able to place new limits of $\mathcal{O}(10^{-15})$ [7] and $\mathcal{O}(10^{-16})$ [1] on the process of $\mu^- \to e^-$ on aluminum respectively, far beyond the 10^{-12} of SINDRUM-II
- Both will also be able to search for $\mu^- \to e^+$ at the same time as $\mu^- \to e^-$
- There are future proposals for both experiments to be able to set limits on $\mu^- \to e^-$ of $\mathcal{O}(10^{-17})$ [7, 8]

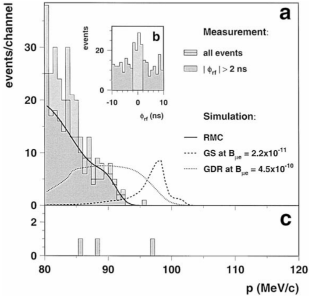
Experimental backgrounds - RMC



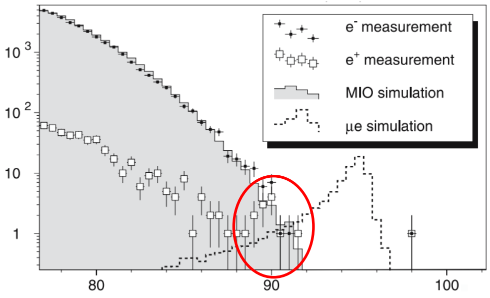
(a) RMC closure approximation (b) 1992 TRIUMF Al data [9]

- Radiative muon capture (RMC) is an irreducible background, where converted or Compton scattered photons can produce signal-like $e^{\pm}$
- The RMC photon energy spectrum is modeled by the closure approximation which only has one parameter: $k_{\max}$, the endpoint of the spectrum [10]
- Fits of existing data consistently result in $k_{\max}$ being several MeV below the kinematic limit [9], though $\mu\ N \to e\ N$ experiments will have $\sim$10 orders of magnitude more RMC photons
- The closure approximation is a simple model though, used to predict the total rates not to model the high momentum region accurately

Previous experimental results (LOI 109)



(a) SINDRUM-II Ti data [6]



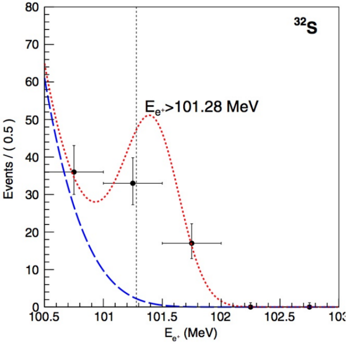
(b) SINDRUM-II Au data [5]

- SINDRUM-II found the closure approximation didn't describe their Ti positron data well
- The positron spectrum in their Au data has an excess in the high momentum tail, that is neither explained well by the closure approximation nor the exotic $\mu^- \to e^+$ process [11]
- These both indicate that RMC in the high momentum region may deviate from the closure approximation
- A better theoretical understanding of the RMC spectrum near the end point, and a high resolution measurement, is needed to take advantage of the power of current and future muon conversion experiments

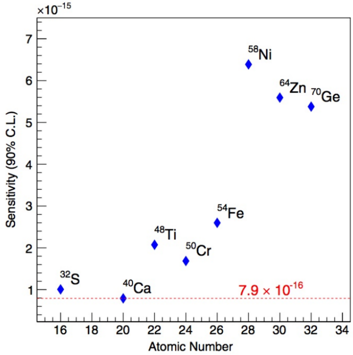
Nuclear target considerations (LOI 108)

- In order to search for $\mu^- \to e^+$ in addition to $\mu^- \to e^-$ at next generation muon conversion experiments, the target should be chosen such that the background from RMC is minimized
- A safe choice is to ask for a nuclear target such that the ground state transition conversion energy for $\mu^- \to e^+$ is greater than the kinematic limit for the RMC photon energy
- This translates into the following requirement on the nuclear masses: $M(Z-2, A) < M(Z-1, A)$
- The medium heavy nuclei that satisfy this requirement are: ^{32}S, ^{40}Ca, ^{48}Ti, ^{50}Cr, ^{54}Fe, ^{58}Ni, ^{64}Zn and ^{70}Ge [12]
- When comparing the search reach between these nuclei, we're forced to make some assumptions about the RMC spectrum
- We could assume a closure approximation using the fit end point values, though this ignores the risk of photons with energies between the fit end point and the kinematic limit

Nuclear target considerations (LOI 108)



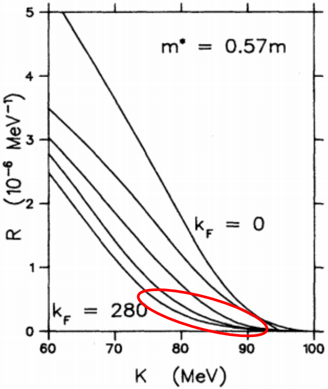
(a) ^{32}S spectrum [12]



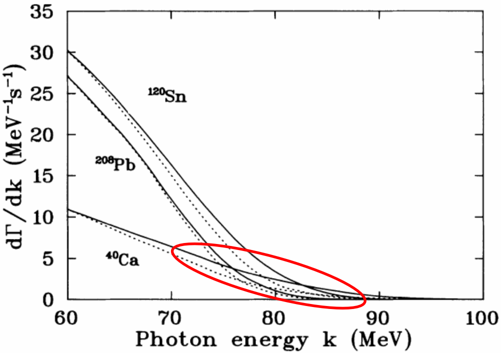
(b) Example sensitivities [12]

- One can use the measured branching ratios but with a closure approximation using the kinematic limit, as a first attempt at understanding the sensitivity reach of future experiments
- As this assumption affects different nuclear targets differently, the experimental reach for different targets may significantly change as the assumed RMC spectrum is changed

Improving theoretical understanding of RMC (LOI 109)



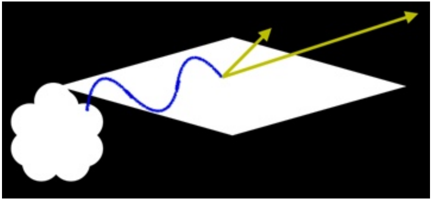
(a) RMC spectra vs k_{Fermi} [13]



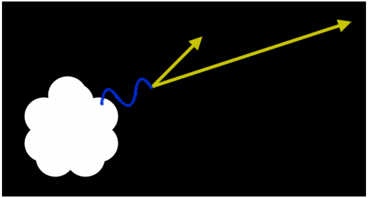
(b) Example RMC spectra [14]

- Fearing et al. used a Fermi gas nuclear model to study the RMC spectra rather than the closure approximation
- The initial plots studied appear to show a long tail in the high energy region, beyond where the closure approximation would cut off

Improving theoretical understanding of RMC (LOI 109)



(a) Real photon conversion in material



(b) Virtual photon conversion

- Theoretical work is underway to recreate the Fearing et al. distributions and better understand expectations and uncertainties near the endpoint [15]
- It's also important study how well can the RMC spectrum be measured at $\mu\ N \to e\ N$ experiments
- In this regard, an expectation for the virtual photon conversion contribution is needed
- If the real photon spectrum is measured, we should be able to predict the positron spectrum near the endpoint from both real and virtual photons [16]

Future work

- RMC is arguably the most uncertain background for $\mu\ N \to e\ N$ experiments
- Better theoretical understanding is needed to study the background for different nuclear targets and explain the existing RMC data
- Studies are needed to understand how well RMC can be measured at $\mu\ N \to e\ N$ experiments
- The next generation experiments should choose a nuclear target with RMC in mind (in addition to other concerns such as muon lifetime, capture rate, etc.)
- Snowmass is a perfect opportunity to study RMC and investigate the possible reach of future/soon-to-run experiments!

Bibliography I

[1] L. Bartoszek et al. Mu2e technical design report, 2015.

[2] W. Marciano, T. Mori, and J. Roney. Charged Lepton Flavor Violation Experiments. Annual Review of Nuclear and Particle Science, 58:315–341, 2008.

[3] Yoshitaka Kuno and Yasuhiro Okada. Muon decay and physics beyond the standard model. Reviews of Modern Physics, 73(1):151–202, Jan 2001. ISSN 1539-0756. doi: 10.1103/revmodphys.73.151. URL http://dx.doi.org/10.1103/RevModPhys.73.151.

[4] Jeffrey M. Berryman, André de Gouvêa, Kevin J. Kelly, and Andrew Kobach. Lepton-number-violating searches for muon to positron conversion. Phys. Rev. D, 95: 115010, Jun 2017. doi: 10.1103/PhysRevD.95.115010. URL https://link.aps.org/doi/10.1103/PhysRevD.95.115010.

[5] Wilhelm H. Bertl et al. A Search for muon to electron conversion in muonic gold. Eur. Phys. J. C, 47:337–346, 2006. doi: 10.1140/epjc/s2006-02582-x.

[6] J. Kaulard et al. Improved limit on the branching ratio of $\mu^- \to e^+$ conversion on titanium. Phys. Lett. B, 422:334–338, 1998. doi: 10.1016/S0370-2693(97)01423-8.

[7] R. Abramishvili et al. COMET Phase-I technical design report. Progress of Theoretical and Experimental Physics, 2020(3), Mar 2020. ISSN 2050-3911. doi: 10.1093/ptep/ptz125. URL http://dx.doi.org/10.1093/ptep/ptz125.

[8] F. Abusalma et al. Expression of interest for evolution of the mu2e experiment, 2018.

Bibliography II

[9] D. S. Armstrong et al. Radiative muon capture on Al, Si, Ca, Mo, Sn, and Pb. Phys. Rev. C, 46:1094–1107, Sep 1992. doi: 10.1103/PhysRevC.46.1094. URL https://link.aps.org/doi/10.1103/PhysRevC.46.1094.

[10] P. Christillin, M. Rosa-Clot, and S. Servadio. Radiative muon capture in medium-heavy nuclei. CERN preprint REF-TH-2967, 1979.

[11] Michael MacKenzie and Pavel Murat. Search for $\mu^- \to e^+$ conversion: what can be learned from the SINDRUM-II positron data on a gold target, 2020.

[12] Beomki Yeo, Yoshitaka Kuno, MyeongJae Lee, and Kai Zuber. Future experimental improvement for the search of lepton-number-violating processes in the $e\mu$ sector. Phys. Rev. D, 96:075027, Oct 2017. doi: 10.1103/PhysRevD.96.075027. URL https://link.aps.org/doi/10.1103/PhysRevD.96.075027.

[13] Harold W. Fearing and G.E. Walker. Radiative muon capture in a relativistic mean field theory: Fermi gas model. Phys. Rev. C, 39:2349–2355, 1989. doi: 10.1103/PhysRevC.39.2349.

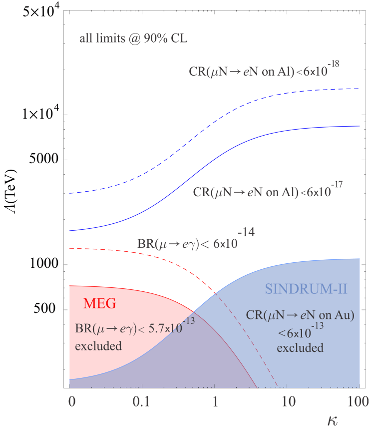
[14] Harold W. Fearing and Mark S. Welsh. Radiative muon capture in medium heavy nuclei in a relativistic mean field theory model. Phys. Rev. C, 46:2077–2089, 1992. doi: 10.1103/PhysRevC.46.2077.

[15] Kaushik Borah, Ryan Plestid, and Richard J. Hill, 2020. Work in progress.

[16] Ryan Plestid and Richard J. Hill, 2020. Work in progress.

Backup slides

Effective lagrangian

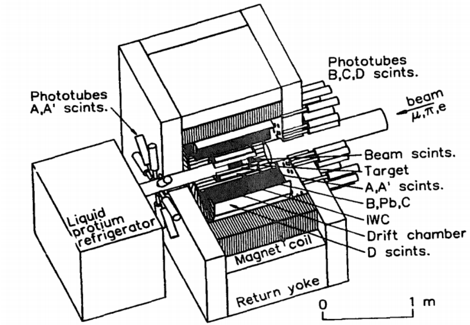


- The figure shows the explored parameter space using the effective Lagrangian:

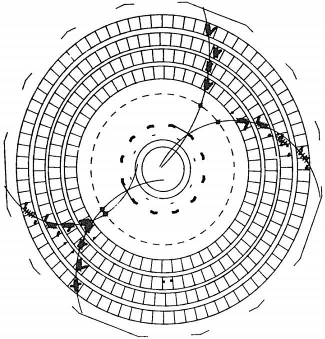
$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L)$$

where Λ is the effective mass scale and κ controls the relative contribution of the magnetic moment term and the four fermion term

TRIUMF RMC spectrometer



(a) TRIUMF detector

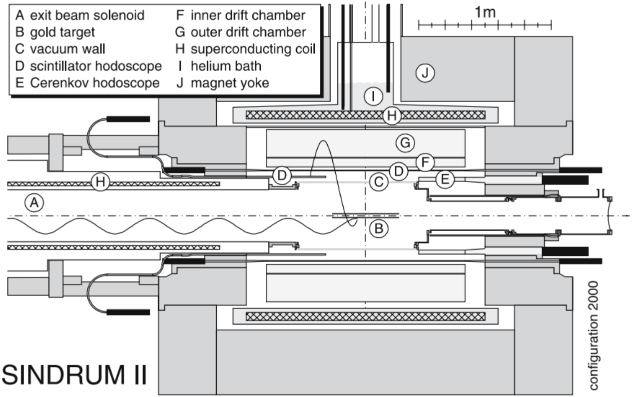


(b) TRIUMF tracking

- In the 1990's, the TRIUMF collaboration measured the RMC spectra of 13 nuclear targets
- They used a tracking spectrometer to measure the photon energies, using a thin lead foil to convert the photons into $e^{\pm}$ pairs that were then reconstructed
- By requiring the $e^{\pm}$ tracks to be consistent with a conversion occurring in the lead converter, they were only reconstructing the real photon spectra for RMC
- They were not sensitive to the virtual photon conversions that would occur in the stopping target
- The TRIUMF data is the largest RMC photon statistics available

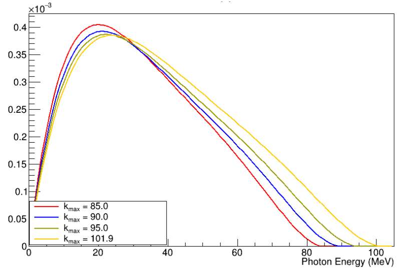
(a,b) Wright et al., 1992

SINDRUM-II experiment

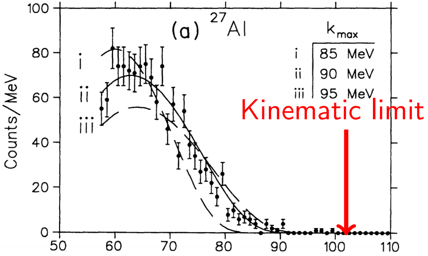


- SINDRUM-II was a previous muon conversion experiment where the current upper limits come from
- RMC was a background for them, where they had higher statistics than TRIUMF near the endpoint of the spectrum
- SINDUM-II only saw the high momentum $e^{\pm}$ from RMC conversions, but was therefore sensitive to both the real and virtual photon contributions to RMC

SINDRUM-II, 2006



(a) RMC closure approximation



(b) 1992 TRIUMF Al data [9]

- The RMC photon energy spectrum is modeled by the closure approximation:

$$\frac{dN}{dx} = \frac{e^2}{\pi}\frac{{k_{\mathrm{max}}}^2}{m_\mu^2}(1-\alpha)\cdot(1-2x+2x^2)\cdot x\cdot(1-x)^2$$

where $x = E_\gamma/k_{\mathrm{max}}$ and $\alpha = (N-Z)/A$ [10]